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Analysis of Photochemical Oxidant and Particulate Pollution Patterns in New England Using Remote Sensing Data

Environmental Research and Technology, Inc, Concord, Mass

Prepared for

Environmental Protection Agency, Boston, Mass Region I

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ANALYSIS OF PHOTOCHEMICAL OXIDANT AND PARTICULATE POLLUTION PATTERNS IN NEW ENGLAND USING REMOTE SENSING DATA

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FINAL REPORT

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16. ABSTRACT

Imagery from earth surveillance satellites is examined to assess the potential usefulness of satellite data for monitoring air pollutant patterns and defining the associated meteorological conditions in southern New England. Three high ozone situations, one high total suspended particulate episode and one high sulfate episode are studied. Imagery from one or more of the following satellite systems: Landsat, NOAA/VHRR, GOES, and DMSP, ranging from the visible to the thermal infrared portions of the spectrum, are visually interpreted for each case. Because of the limited data sample, it is difficult to derive firm conclusions for particular imagery types or specified pollutants. Nevertheless, the results of the study indicate that there is a good correlation between certain types of high pollutant load (including ozone and sulfates) and haze and smoke, with accompanying reductions in visibility. There is good evidence that satellite imagery can display differences in reflectance (visible) or temperature (thermal infrared) due to some combination of haze, smoke and atmospheric pollutant load, on a regional basis. The greatest promise was shown by the DMSP thermal infrared imagery in application to high sulfate situations.

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FINAL REPORT

Prepared for

Environmental Protection Agency
Region I
Air Branch
JFK Federal Building
Boston, Massachusetts 02203

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FOREWORD

The investigation described herein was performed by Environmental Research & Technology, Inc. (ERT) for Region 1, Air Branch of the Environmental Protection Agency under Contract No. 68-02-2533.

The authors acknowledge the guidance provided by Mr. Valentine J. Descamps, the EPA Project Officer. Data from the SAROAD data network was provided by EPA, Region 1. The authors are extremely grateful to Mr. Eugene Y. Tong of ERT for his assistance throughout this project and many helpful suggestions, and for providing the regional sulfate data used in the study.

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1. INTRODUCTION

1.1 Purpose of Study

The purpose of this investigation was to examine the potential usefulness of satellite data for monitoring air pollutant patterns and for defining the associated meteorological conditions in southern New England. The principal objective of Task 1 was to conduct analyses of Landsat and meteorological satellite data (NOAA/VHRR and GOES) during three episodes of high photochemical oxidant levels over southern New England as reported by the EPA's "SAROAD" data network.

The completion of Task 2 was initially directed toward analyses of Landsat data during two episodes of high total suspended particulate (TSP) levels over New England as reported by the "SAROAD" network. However, problems such as cloud contamination and isolated high TSP readings suggesting influence of local fugitive dust rather than overall high TSP events became apparent; therefore, it was mutually agreed (ERT and EPA Project Officer) that further analyses of TSP episodes would be replaced by analysis of one or two incidents of high sulfate concentrations over the Northeast utilizing meteorological satellite data.

1.2 Review of Previous Studies

The ability to detect certain types of air pollution patterns from satellite imagery has been noted by a number of investigators. McLellan (1971) successfully correlated a series of ATS-3 satellite images of reflected radiation from the City of Los Angeles at 40 minute intervals on 23 April, 1968 with various ground based meteorological data. The analysis of the data indicated the feasibility of satellite monitoring of short-term atmospheric pollution variation over large urban areas. Prospero, et al. (1970) showed the feasibility of satellite monitoring of global scale movements of natural pollution. In this study, a series of ATS-3 images were correlated with aircraft and ship sampling data of dust being transported by air currents from the arid and semi-arid regions of North Africa across the Atlantic to the Caribbean during the summer of 1969.

Recently, the utilization of improved satellite imagery as a means for monitoring environmental quality has been further realized. Lyons and Northouse (1973) showed that the interaction of air pollution and meteorological conditions over the Great Lakes led to inadvertant weather modification detectable in Landsat imagery. Griggs (1973) found that radiance measurements over water could be used successfully to calculate the vertical aerosol burden to an accuracy approaching ±10%. In a more recent investigation, Brown and Karn (1976) examined the usefulness of Landsat imagery for detecting sources of air pollution resulting from coal utilization in the Ohio and Monongahela River valleys south of Pittsburgh, Pennsylvania. This area is heavily industrialized and includes many coal-fired power-generating stations. In this investigation, large billowy steam plumes from specific point sources were identified in Landsat imagery.

In addition, Lyons and Husar (1976) reported the likely detection of a synoptic-scale sulfate air pollution episode over the central and eastern United States in SMS/GOES visible images. It was shown that image "haziness" correlated well with midday surface visibility reports, which in turn appeared to correlate with sulfate aerosol concentrations. Unfortunately, Lyons and Husar were not able to show the regional extent of the high sulfate eposode, probably because the available sulfate measurements were only for a limited area.

1.3 Description of Satellite Data

The satellite data obtained for the completion of this study program included imagery from the Landsat, NOAA/VHRR, GOES and DMSP satellite systems. The wide variety of imagery provided by these various experimental and operational spacecraft are defined in the following paragraphs.

1.3.1 Landsat

The initial spacecraft in the experimental Landsat series was placed into orbit at a height of 900 km in late July 1972 and was called at that time ERTS-1, the Earth Resources Technology Satellite. The second spacecraft, Landsat-2, was placed into operation in January

1975. Each satellite repeats coverage of the same area only once every 18 days; however, Landsat-2 was placed into orbit such that coverage of the same area was being provided by one of these spacecraft every nine days. A recent orbital adjustment has resulted in repeat coverage on a six- and 12-day cycle.

The Landsat Multispectral Scanner Subsystem (MSS) observes in four spectral bands within the visible-to-near infrared portions of the spectrum (MSS-4, 0.5-0.6 μm; MSS-5, 0.6-0.7 μm; MSS-6, 0.7-0.8 μm; and MSS-7, 0.8-1.1 μm). Therefore, Landsat observations are available only during periods of adequate solar illumination. Landsat views an area approximately 185 km on a side, per image frame, as it proceeds along its orbital path, and has a resolution of 70-100 meters. The scale of the standard Landsat 9 inch x 9 inch prints is 1:1 million.

1.3.2 NOAA/VHRR (Very High Resolution Radiometer)

The VHRR sensor has been flown on the NOAA-2, NOAA-3, NOAA-4, and NOAA-5 spacecraft, so that the resulting data have been available on a nearly continuous basis (one or two observations per day) since January 1973. The VHRR is a two-channel radiometer, with one channel sensitive to reflective solar radiation in the 0.5-0.7 μm wavelengths, and the other channel measuring the thermal radiation emitted by clouds and the earth's surface in the infrared 10.5-12.5 μm wavelengths. The spatial resolution of the VHRR is about 1 km. The scale of the standard size prints is approximately 1:10 million.

The VHRR is designed primarily for direct readout use as an operational meteorological satellite. The area that can be observed when the satellite passes directly overhead is a strip about 2,200 km wide and more than 5,000 km long. This allows broad overall synoptic weather patterns to be determined from each individual scene.

1.3.3 GOES (Geostationary Operational Environmental Satellite)

Another type of operational meteorological satellite data is provided by the GOES system. Launched on 16 May 1974, GOES-1 is stationed over the equator in an earth synchronous orbit in a position to view the eastern United States and Atlantic Ocean. Because of its earth

synchronous orbit, GOES provides coverage of the earth's disc on an essentially continuous basis, with data being collected every one-half hour. Thus, cloud motions can be tracked and storm development can be monitored; using the cloud motions, it is possible to derive low-level wind flow. As with the VHRR, the GOES sensor system carries a thermal infrared channel for obtaining nighttime data. The visible channel radiometer operates in the 0.55 to 0.70 μm wavelength at a spatial resolution of 1 km, whereas the infrared channel operates in the 10.5 to 12.5 μm wavelength at a resolution of 7 km.

1.3.4 DMSP (Defense Meteorological Satellite Program)

The Air Force DMSP is an operational satellite system useful for providing meteorological and oceanographic data. These polar orbiting, sun synchronous weather satellites are positioned 900 km above the earth. In the operational mode, the DMSP satellites provide imagery every 6 hours over any spot on earth. The imagery includes the visual to near infrared and thermal infrared spectral intervals over a 3,000 km wide swath below the satellite.

Real time meteorological data within the acquisition range of the satellite signal, approximately a radius of 2,800 km of the receiving station, are provided to military sites. These sites are scattered around the globe and on board U. S. Navy aircraft carriers. The Air Force Global Weather Center (AFGWC) at Offutt Air Force Base, Nebraska, receives stored data of global coverage; these data have been available to nonmilitary users since 1972, and are archived at the University of Wisconsin. The visible to near infrared wavelength channel has a spectral interval of 0.4 to 1.1 μm with a spatial resolution of 0.6 km; the thermal infrared channel operates in the 8 to 13 μm wavelength with a spatial resolution of 3 km. Scale of the standard prints is 1:10 million.

2. ANALYSIS PROCEDURES - PHOTOCHEMICAL OXIDANTS/OZONE

2.1 Data Sample

The three episodes of high photochemical oxidant levels over southern New England selected for analysis were initially included on a listing of high episodes supplied by the EPA-Region 1, Air Branch. Each of the episodes was examined to determine the availability of useful, cloud-free Landsat imagery. A computer listing supplied by the EROS Data Center, Sioux Falls, South Dakota, showed that useful Landsat data were available for only two of the episodes. The correlative satellite data available for the other episode selected for analysis included only the NOAA/VHRR and GOES imagery.

The three episodes of high photochemical oxidant levels analyzed in this investigation consisted of the following spring and summertime periods of 1975: 20-23 May; 23-24 June; and 23-24 July. Correlative Landsat imagery were available for 20 May and 23 July. The MSS-4 70 mm positive transparencies for these dates were obtained from the U. S. Army Corps of Engineers (Waltham, Massachusetts) browse file, and standard size, 9 inch x 9 inch (1:1 million scale), as well as enlarged (approximately 1:500,000 scale), positive paper prints were processed in ERT's photographic laboratory. The MSS-4 visible band was used in each case because past experience has shown that this is the most useful band for detecting pollution and haze. Much of the evidence of this has come from investigators of earth surface features who have found these features to be more susceptible to obscuration by atmospheric conditions in Band 4 than in any other band. Also, all available NOAA/VHRR (visible and infrared) and GOES (visible) imagery viewing the New England region during the periods of each episode were obtained from the NOAA-Satellite Data Services Branch, World Weather Building, Camp Springs, Maryland.

Listings of the EPA's 1975 SAROAD data for Massachusetts, Connecticut and Rhode Island were obtained from the EPA's facility in Lexington, Massachusetts. The ozone concentrations measured closest to the times of the satellite images were plotted and analyzed on area base maps. The comparisons of maximum ozone concentrations with the correlative

satellite imagery and associated meteorological conditions for each of the episodes are discussed in the following sections.

2.1.1 Case 1, 20-23 May 1975

Hourly ozone concentrations at times corresponding to the readout times of the correlative Landsat and NOAA/VHRR satellite images (~1500 GMT, 1000 LST), generally exceeded the national ambient air quality primary and secondary standard of 0.080 ppm over broad areas of southern New England. However, analyses of ozone concentrations during this period revealed a definite diurnal trend with maximum concentrations occurring during the mid to late afternoon hours. Analysis of the ozone concentrations over southern New England at 1500 GMT on 20 May is shown in Figure 2-1. Maximum concentrations, exceeding 0.140 ppm, are located in extreme southwestern and southeastern Connecticut, while another relatively high concentration, exceeding 0.120 ppm, is located immediately north and east of Boston.

A mosaic of two Landsat, MSS-4, images viewing this region at 1440 GMT on this date is shown in Figure 2-2. In this image, no variations in brightness are detectable over the land area that could be attributed to the high ozone concentrations. However, in the original photographic prints used in the analysis some increased brightness levels [likely associated with reported low visibilities in haze (less than 5 miles) and possibly, high ozone] are observed over the darker water areas of Long Island Sound and to the east of Boston and Cape Ann. Over the land area, any varying degree of image brightness due to air pollution density is likely obscured by the varying brightness levels of ground-feature reflectivities (most notably, the dense urban developments which appear highly reflective in the images). No useful NOAA or GOES imagery was available for this date.

Isolated high concentrations of ozone at a somewhat lesser peak value (but still >0.080 ppm) remained over portions of the region during 21 and 22 May; however, no features were detectable in either the NOAA/VHRR or GOES imagery on these dates because of cloud contamination. Analysis of the SAROAD ozone data for 1400 GMT on 23 May (Figure 2-3) showed a broad band of maximum concentration (>0.120 ppm) located in west central Connecticut, and an isolated small pocket (>0.100 ppm)

located just to the west of Boston. The correlative NOAA/VHRR visible image (1401 GMT) for this date is shown in Figure 2-4. Although dense, offshore fog is observed surrounding the southern New England coastal regions from Long Island Sound into the southern Gulf of Maine, no features associated with the maximum ozone concentrations are observed on the image. The band of higher reflectance, located near the area of highest ozone concentration in Connecticut, is again associated with dense urban development in the Connecticut River Valley.

Examination of the meteorological conditions during this period showed a generally light, southerly flow of warm, moist, tropical air associated with a near stationary ridge of high pressure extending from well off the middle Atlantic coastal region, southwestward across the entire southeastern United States. The importance of heat and moisture becomes more apparent when examining the late morning surface temperatures and corresponding dew point temperature readings. During the beginning of the period (20 and 21 May), late morning surface temperatures ranged between 80° and 85°F across southern New England except for extreme southern coastal sections where temperatures remained in the mid-70's due to the effect of the light southerly wind flow from the cooler ocean waters. Corresponding dewpoint temperatures were generally in the middle 60°F range at these times.

The slight reduction in peak ozone concentrations observed on 22 May was likely the result of a weak "back door" cold front that moved westward across New England into eastern New York State during the morning hours, before retreating eastward again as a warm front early on the 23rd. During the early afternoon hours on 23 May, when the highest ozone concentrations for the entire period were observed, surface temperatures ranged between the upper 80's to low 90's, with dewpoint temperatures ranging from the upper 60's to low 70's.

Throughout the period, broadscale haziness resulting in reduced visibilities accompanied the high ozone concentrations. This finding is consistent with a report by Husar, et al. (1976), in which he mentions that broad areas of haziness and reduced visibilities accompanied high mid-day ozone concentrations that exceeded the national ambient air quality standard in the St. Louis metropolitan area during summertime periods of 1975. With this in mind, area base maps of skycover, winds,

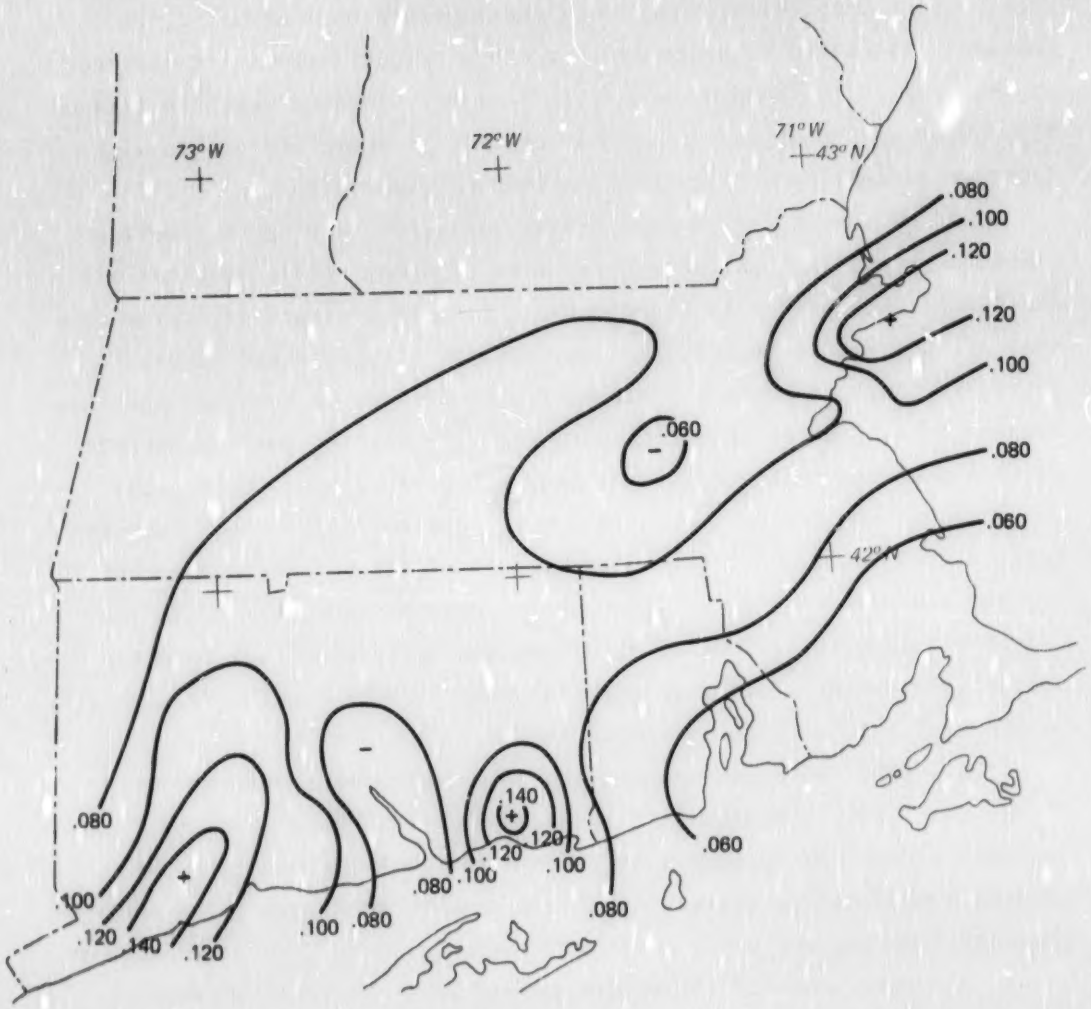

Figure 2-1 Analysis of ozone concentration (ppm) over southern New England at 1500 GMT, 20 May 1975

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Figure 2-2 Mosaic of Landsat-1, MSS-4 imagery viewing southern New England at 1440 GMT, 20 May 1975

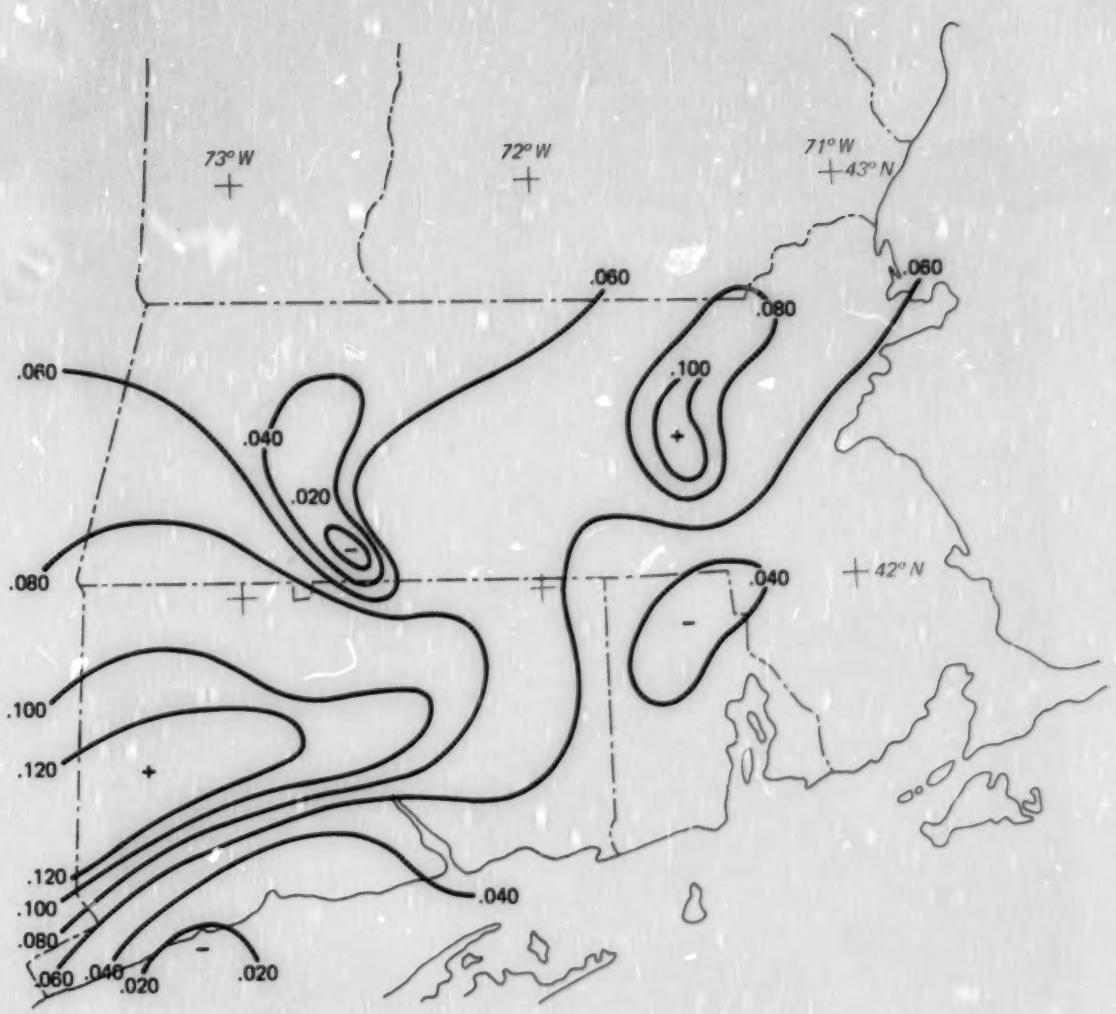

Figure 2-3 Analysis of ozone concentration (ppm) over southern New England at 1400 GMT, 23 May 1975

Figure 2-4 NOAA/VHRR daytime visible image viewing the northeastern United States at 1401 GMT, 23 May 1975

and visibility were plotted from the weather reports for the period of 18 May through 23 May. The 1600 GMT hourly reports were chosen to reduce the effect on visibilities by early morning fog conditions. Analyses of the reported visibilities suggested an overall long range transport of haziness and smoke into southern New England from the New Jersey, Maryland and eastern Pennsylvania area during the period, as well as some probable in situ development over southern New York State and western Long Island. The extent of minimum visibilities of from 1.5 to 2 statute miles in haze and smoke for much of Connecticut on 23 May, shown in Figure 2-5, compares well with the extent of maximum ozone levels of from 0.150 to 0.205 ppm reported for this region at 1800 GMT on this date (Figure 2-6).

2.1.2 Case 2, 23-24 June 1975

The ozone concentrations as reported by the SAROAD data base for Massachusetts, Connecticut and Rhode Island at the corresponding image times (NOAA/VHRR - 1438 GMT, and GOES - 1800 GMT) for the period of 23 and 24 June 1975 were plotted on area base maps and analyzed. No Landsat imagery was available for either of these days. These analyses, as in the previous case, showed a marked increase in ozone concentration at the later time period (1800 GMT), especially on 23 June when maximum levels increased nearly 200%, from about 0.100 ppm to 0.280 ppm over the 4-hour period.

A plot of skycover, winds and visibility for 1600 GMT for 22, 23, and 24 June suggested some long range transport of pollutants into southern New England from New York State and Pennsylvania, as well as probable in situ pollution development. Areas of minimum visibilities of 2 to 4 miles in haze reported for much of Connecticut on 23 and 24 June (Figures 2-7 and 2-8) correlate well with the locations of maximum ozone concentrations.

With one exception, no evidence of the maximum ozone concentrations over southern New England was detectable on the NOAA/VHRR or GOES imagery of either day. The exception is the NOAA-4 visible image of 24 June, shown in Figure 2-9. This image was acquired along a satellite track positioned far enough to the west to display a low sun angle along the middle Atlantic coast from about Cape Hatteras to southern New

England. Therefore, the area of low visibility in haze and smoke (2-4 miles) located over New Jersey, Pennsylvania, southeastern New York State and Connecticut is easily detected due to illumination by the sun. The extent of the low visibility area observed over Connecticut agrees well with the location of the maximum ozone concentration as reported by the SAROAD network. Of all of the satellite imagery examined, this NOAA image revealed the only detectable evidence of high pollution concentration associated with peak ozone concentrations over land areas. Sun angle apparently plays an extremely important role in the ability of satellites to detect high pollution concentrations and associated low visibilities in the visible portions of the spectrum.

Examination of the overall synoptic meteorological pattern during this period revealed the dominance of a warm, humid maritime tropical air mass throughout the entire region. A near-stationary high pressure system (anticyclone) was positioned just off the middle Atlantic coastal region resulting in the flow of warm, moist air into New England on light to moderate (10-15 knots) southwesterly winds. Daytime high temperature readings of from the upper 80° to low 90°F range were experienced over southern and central New England on each of the days, and dewpoint temperatures climbed into the low 70°F range.

2.1.3 Case 3, 23 July 1975

The hourly ozone concentrations closest to the time of correlative Landsat imagery (1500 GMT) on this date are shown in Figure 2-10. The analysis of the ozone distribution reveals a band of maximum concentration (>0.120 ppm) extending from extreme southwestern Connecticut northward to near Waterbury with amounts in excess of 0.080 ppm extending as far north as Hartford. Other areas of southern New England reported amounts generally between 0.050 and 0.070 ppm.

The Landsat MSS-4 image viewing the area on 23 July is shown in Figure 2-11. Again, as discovered in Case 1, the Landsat imagery reveals no indication of the band of maximum ozone levels over land areas; however, evidence of the reduced visibilities in haze being reported from Bridgeport, Connecticut, eastward to Block Island, Rhode Island, is readily detectable (in the original photographic prints) over the darker water area of Long Island Sound. Reduced visibilities in haze and smoke have accompanied each of the high photochemical oxidant episodes being examined.

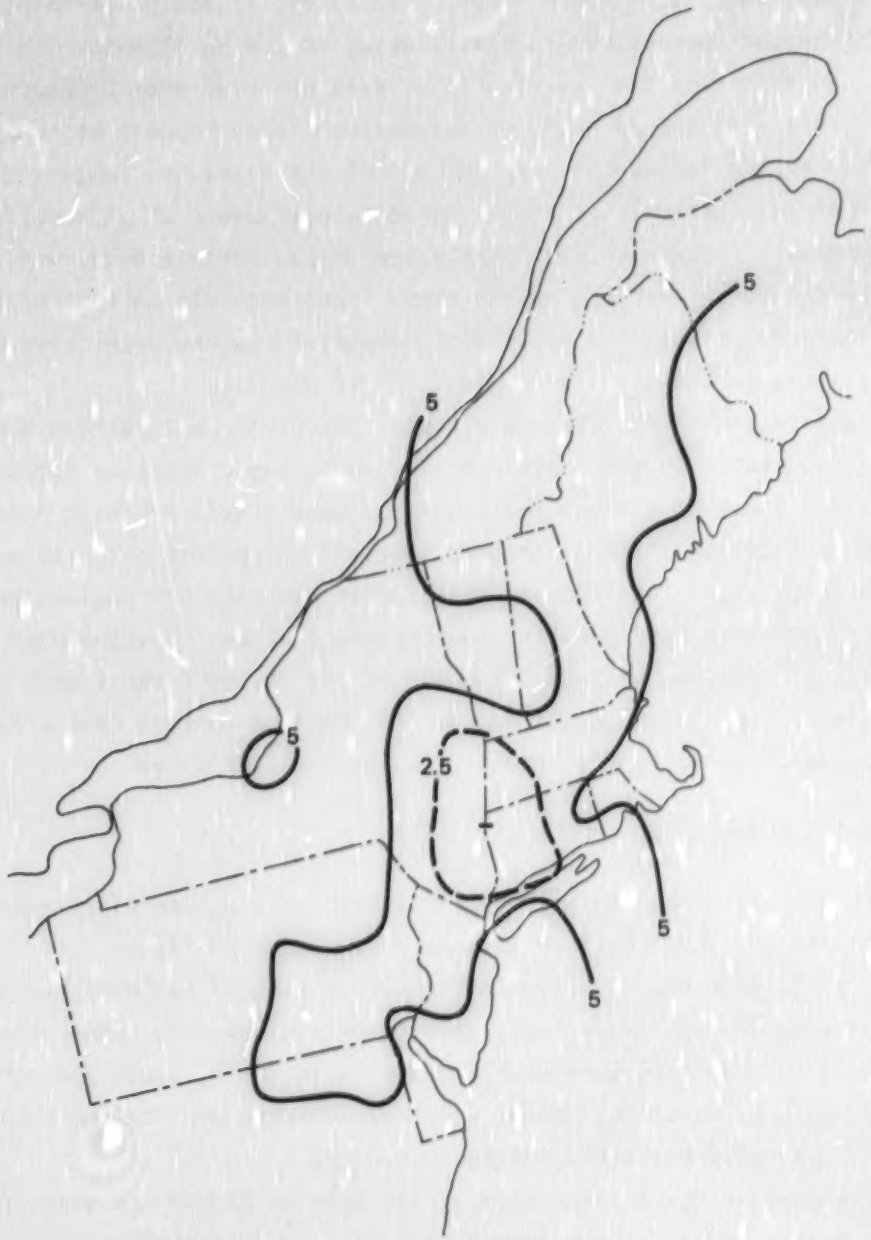

Figure 2-5 Map displaying the extent of reduced visibilities (statute miles) in haze and smoke over the northeast at 1600 GMT, 23 May 1975

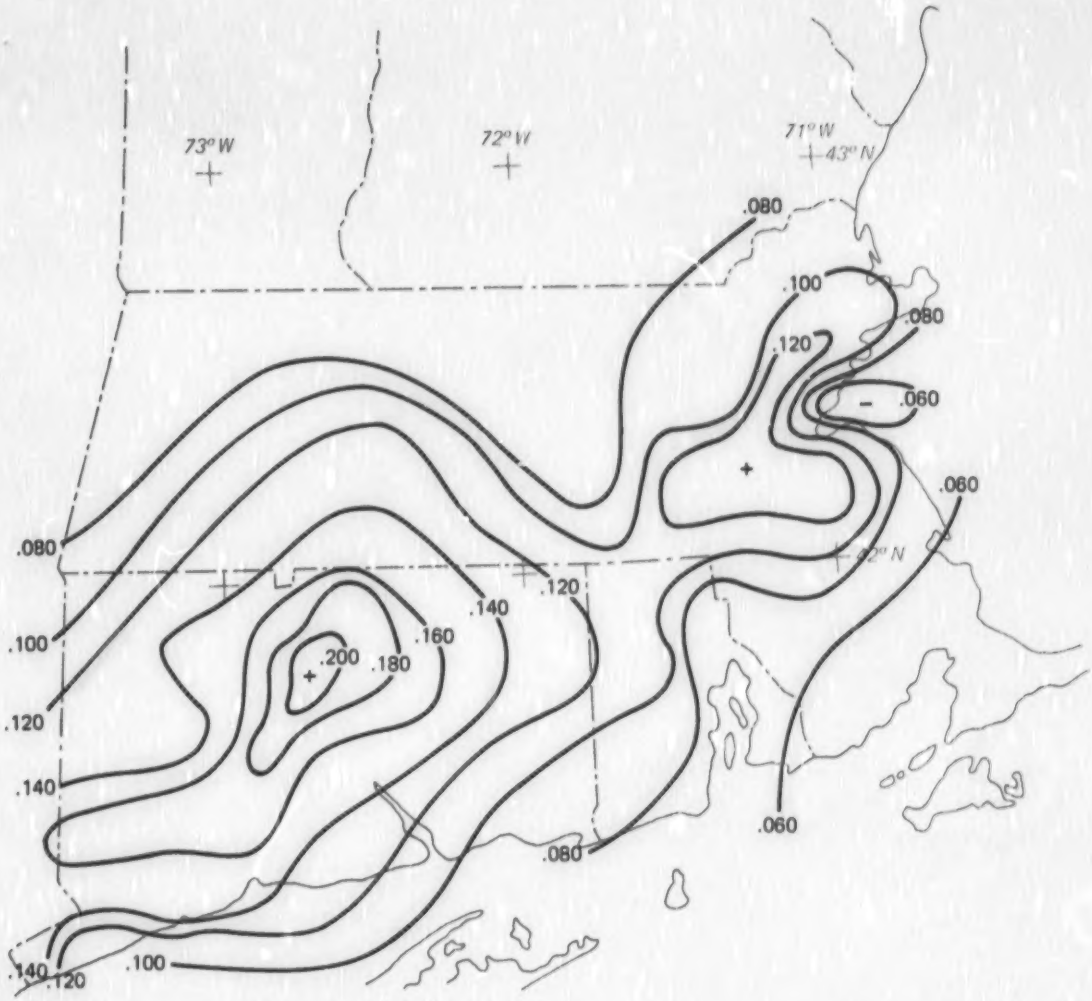

Figure 2-6 Analysis of ozone concentration (ppm) over southern New England at 1800 GMT, 23 May 1975

Figure 2-7 Map displaying the extent of reduced visibilities (statute miles) in haze and smoke over the Northeast at 1600 GMT, 23 June 1975

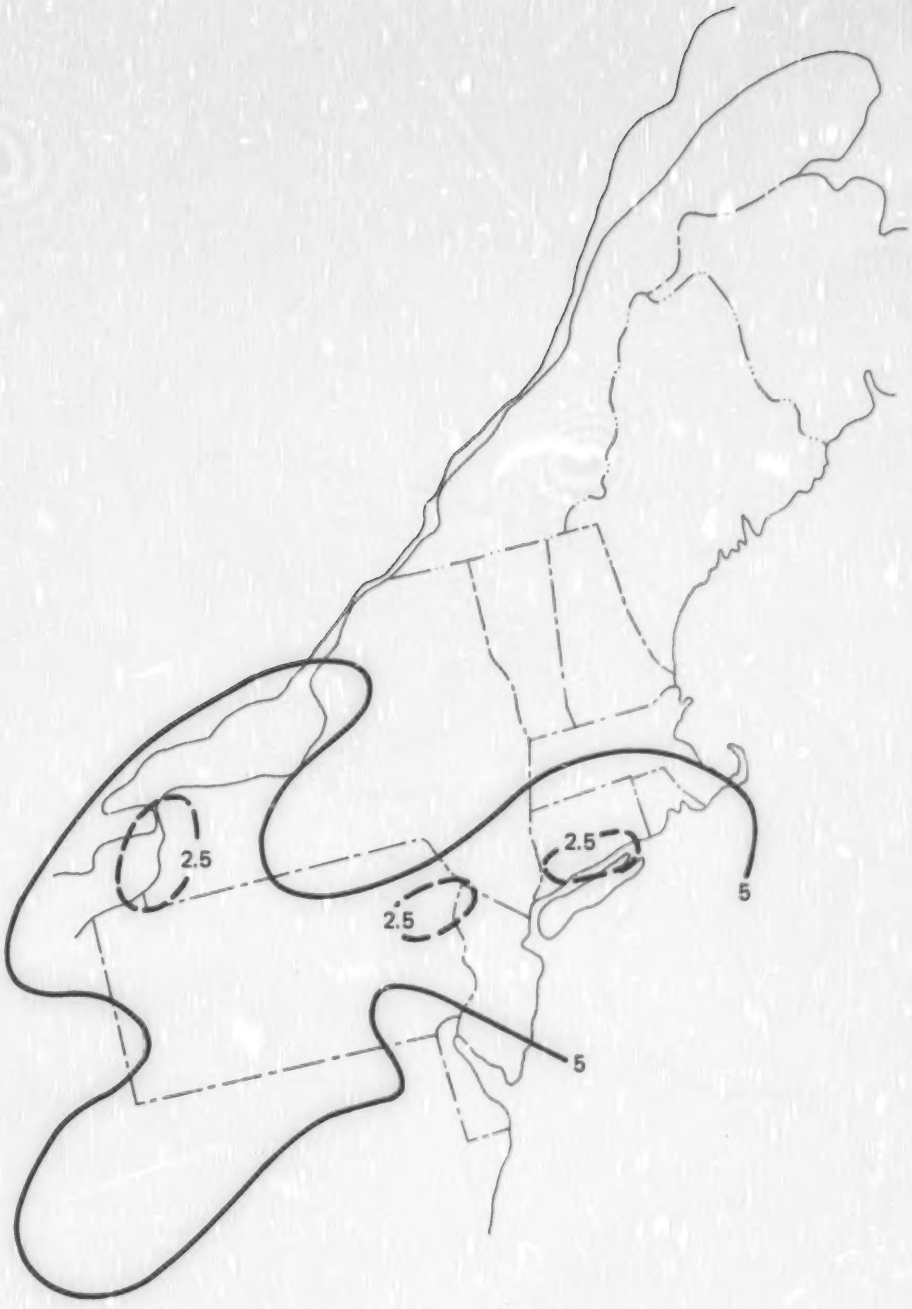

Figure 2-8 Map displaying the extent of reduced visibilities (statute miles) in haze and smoke over the Northeast at 1600 GMT, 24 June 1975

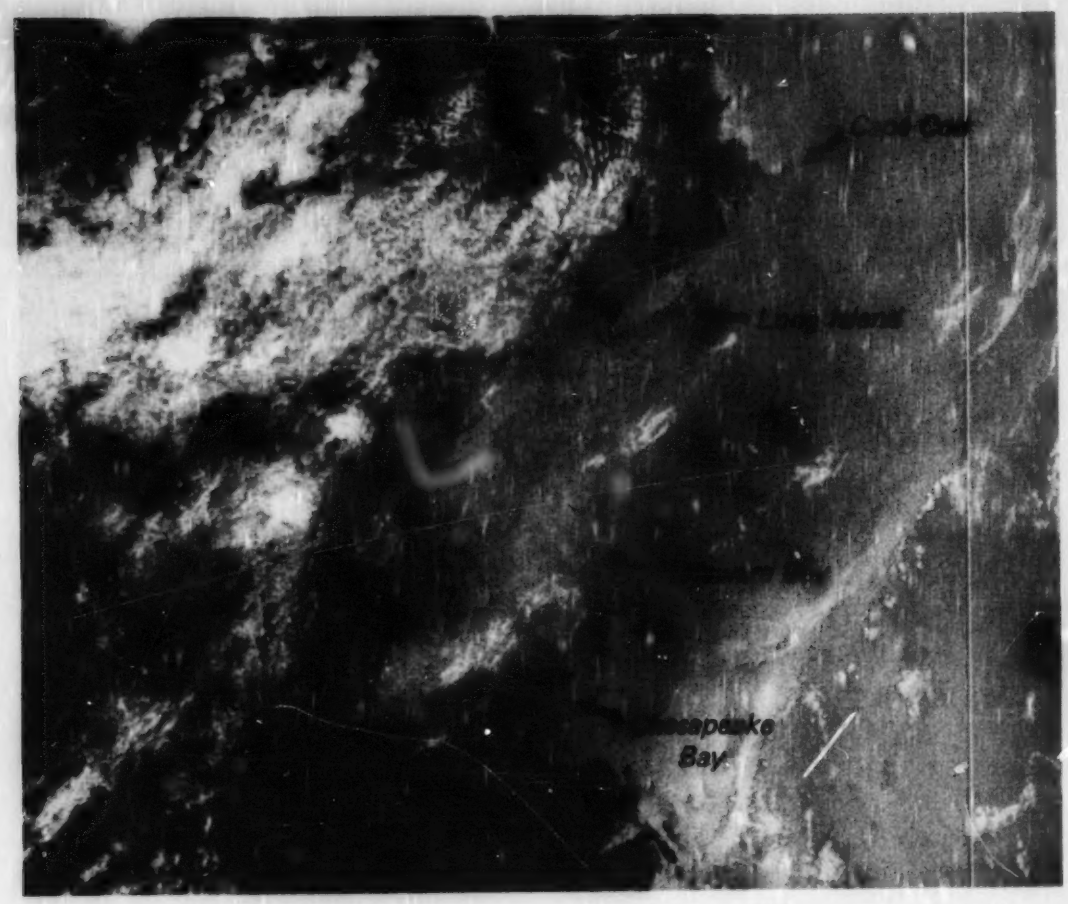

Figure 2-9 NOAA/VHRR daytime visible image viewing the northeastern United States at 1439 GMT, 24 June 1975. A region of low visibility in haze and smoke located over this region is easily detected due to illumination by the sun.

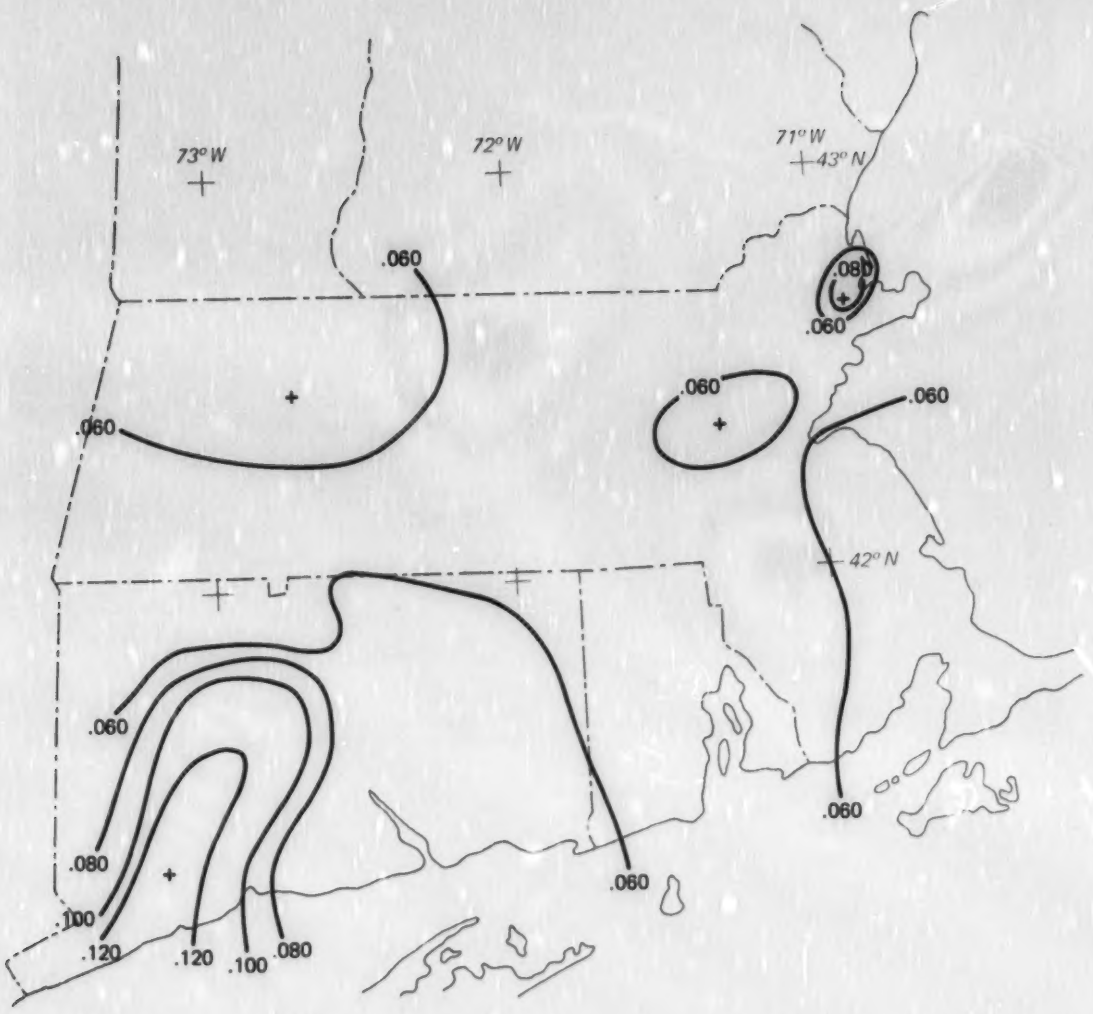

Figure 2-10 Analysis of ozone concentration (ppm) over southern New England at 1500 GMT, 23 July 1975

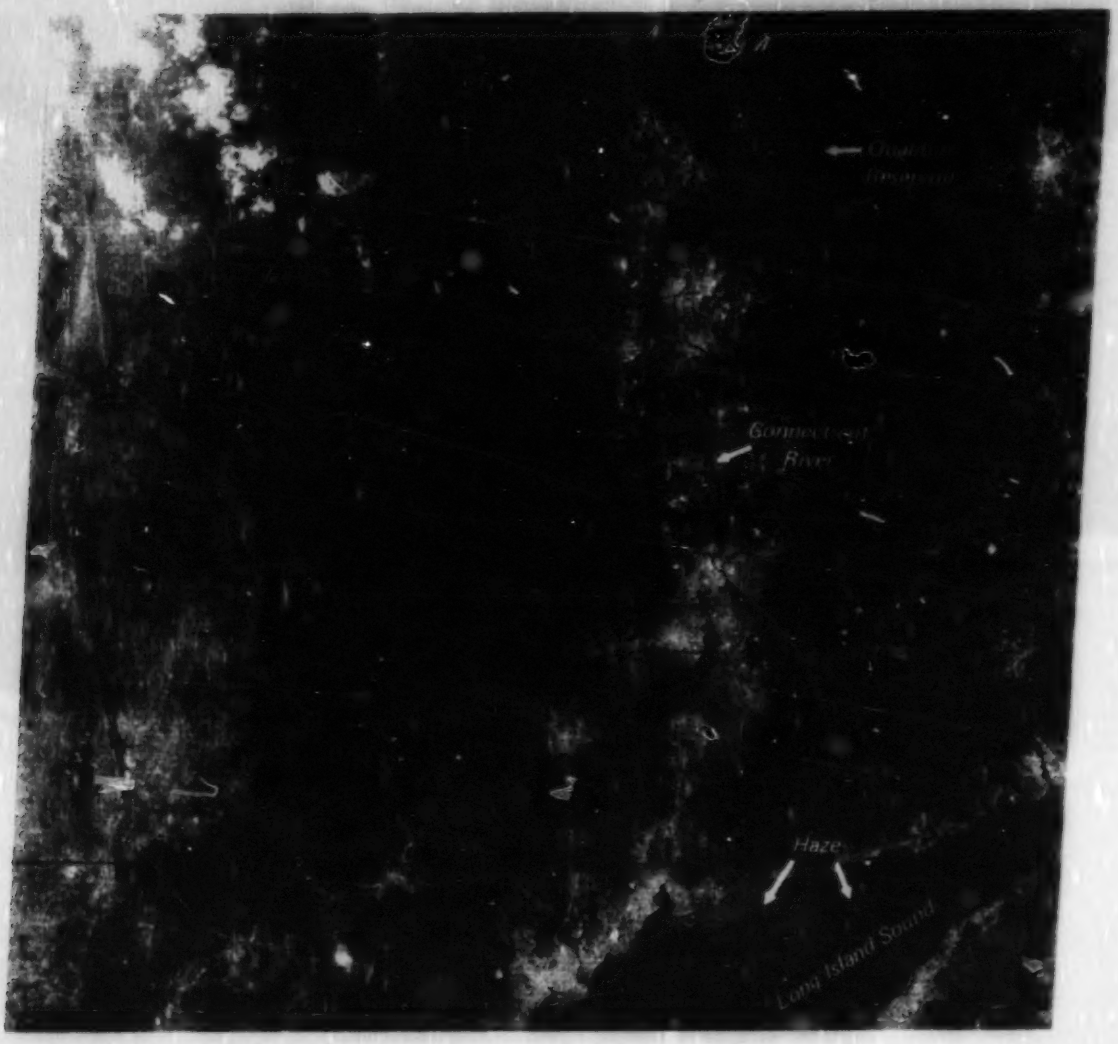

Figure 2-11 Landsat-2, MSS-4 image viewing Connecticut and eastern Long Island Sound at 1455 GMT, 23 July 1975

The synoptic meteorological conditions associated with this episode were also analogous to the previous two cases. Examination of the 23 July surface charts showed a nearly stationary ridge of high pressure centered well to the southwest near Virginia. Therefore, a warm, moist flow of air on light to moderate southwesterly surface winds was experienced over southern New England. Maximum surface temperatures reached the low 80's across extreme southern coastal sections and the upper 80°F range over northern Connecticut and Massachusetts. Corresponding dew point temperatures ranged from the mid to upper 60°F level throughout the region.

3. ANALYSIS PROCEDURES - TOTAL SUSPENDED PARTICULATES (TSP)

3.1 Data Sample

Examination of correlative Landsat coverage during a number of periods of high total suspended particulate (TSP) levels over southern New England during 1974 and 1975 showed that no data were acquired by Landsat during any of the episodes. Therefore, a computer query search was requested from the EROS Data Center, Sioux Falls, South Dakota, for a listing of Landsat coverage of central and southern New England for all dates with less than 50% cloud cover. A check of this computer listing for dates of useful Landsat coverage showed that correlative SAROAD TSP data (recorded every six days) was available for only two of the dates, 4 April and 6 May 1976. A check of the 1976 SAROAD data, obtained from the EPA facility in Lexington, revealed low TSP levels on 4 April; however, three small pockets of relatively high TSP levels (exceeding national ambient air quality secondary standard of 150 $\mu g/m^3$ for 24-hour average) were found to exist over southern New England on 6 May 1976.

Although no Landsat coverage was available for two dates of reportedly high TSP concentrations over southern New England (24 January and 18 April 1975), NOAA/VHRR and GOES imagery were obtained to determine if the lower resolution of these satellites was at all useful for detecting the high TSP events. Unfortunately, the imagery was not useful because of cloud contamination over the region on each of these dates.

The 24-hour average values of TSP were plotted and analyzed on area base maps for 6 May 1976, the one case for which correlative Landsat data existed. A comparison of the TSP analysis with the Landsat satellite data is discussed in the following section.

3.2 Data Analysis for 6 May 1976

Analysis of the 24-hour average values of TSP as reported by the EPA's SAROAD data network is shown in Figure 3-1. This analysis reveals that the highest concentrations were confined to isolated small areas in central Connecticut, near Springfield, Massachusetts, and over Providence, Rhode Island, where values generally exceeded 150 $\mu g/m^3$.

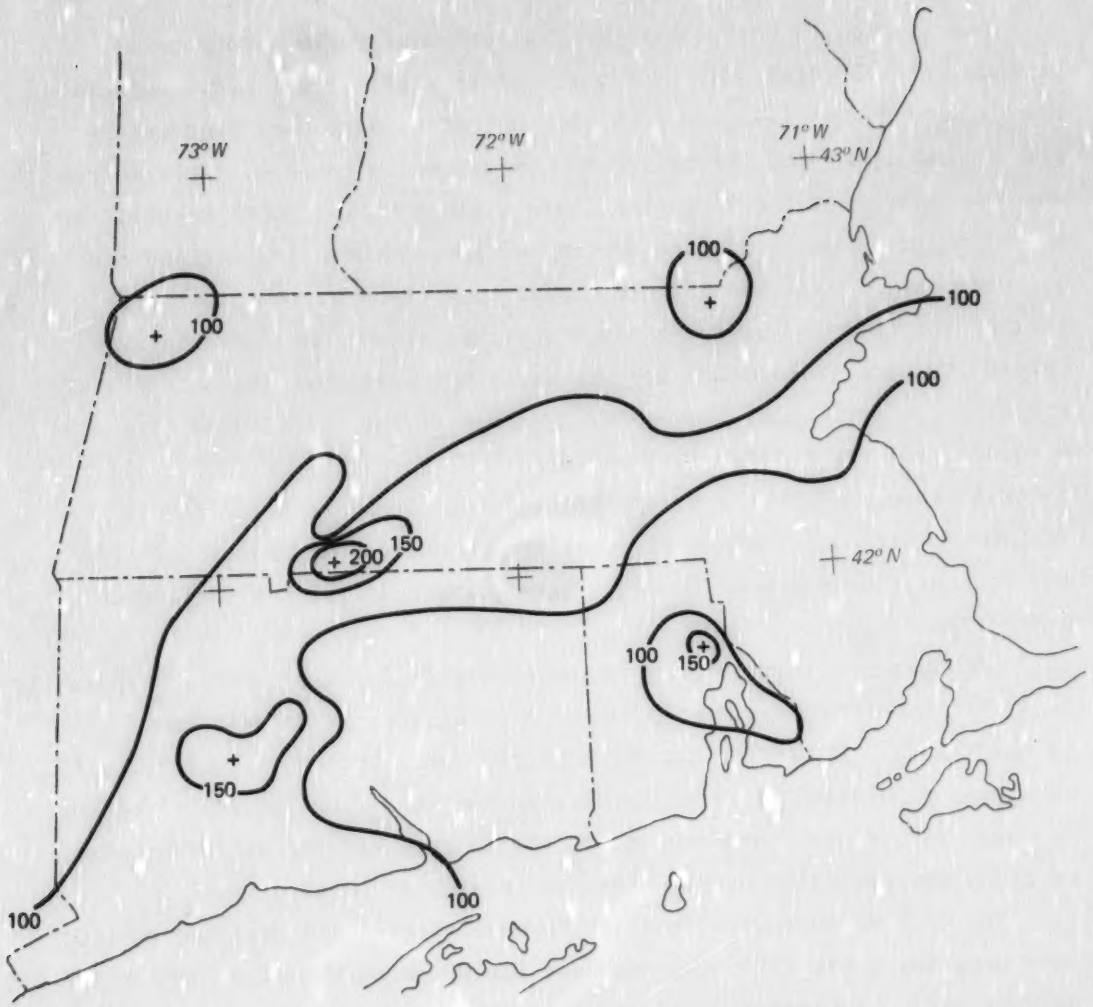

Figure 3-1 Analysis of 24-hour average values of total suspended particulates (ug/m^3) over southern New England on 6 May 1976

Figure 3-2 Landsat-2, MSS-4 image viewing Connecticut and south central Massachusetts at 1450 GMT, 6 May 1976

The correlative Landsat image (1450 GMT), shown in Figure 3-2, views the areas of high TSP levels located in central Connecticut and near Springfield, Massachusetts. This image shows a thin veil of high cloudiness (cirrostratus) obscuring much of the area of high TSP (>200 $\mu g/m^3$) located over Springfield. Examination of the 1500 GMT hourly weather data revealed that most stations in southern New England were reporting high, thin clouds. The small pocket of high TSP (>150 $\mu g/m^3$) located over central Connecticut lies under generally clear skies; however, no distinct reflectance boundaries associated with the maximum TSP concentration are observed in the image.

Although the isolated pockets of high TSP on this date fall within a narrow band of relatively high TSP levels (>100 $\mu g/m^3$), which extends northward across Connecticut and then to the east-northeast across Massachusetts (Figure 3-1), it is possible that the high readings reflect the actual influence of local fugitive dust (such as from roadways and gravel areas) rather than the ambient TSP conditions. Also, the precise times of the occurrence of high TSP levels on this date, which contributed to the overall high 24-hour average values, could have taken place much later in the day, and not near the time of the Landsat image.

Analysis of the 1500 GMT hourly surface weather data revealed a cold front advancing slowly southeastward across northern areas of New England at the time of the Landsat image, with a moderate (15 to 20 knots) south to southwest surface wind flow regime over southern New England. This surface wind flow pattern agrees remarkably well with the orientation of the band of maximum TSP levels (>100 $\mu g/m^3$) observed in Figure 3-1. Further examination of the ensuing hourly weather information showed that this wind pattern prevailed throughout much of the remainder of the day.

The correlative NOAA/VHRR and GOES imagery on this date revealed no features suggesting association with the locations of the maximum TSP levels.

4. ANALYSIS PROCEDURE - SULFATES (SO_4)

4.1 Data Sample

Because of the difficulty of identifying useful correlative Landsat imagery, plus possible TSP sampler location problems affecting the completion of the Task 2 phase of this investigation (see Section 3), a modification of the original work statement was requested. It was subsequently agreed by the EPA Project Officer that further analysis of TSP episodes would be deleted. Instead, an analysis of one or two incidents of high sulfate concentrations over the Northeast would be undertaken with comparisons being conducted with correlative meteorological satellite imagery. The rationale for examining regional sulfate episodes with corresponding satellite-observed haze layers was provided by several recent regional air pollution studies. Husar, et al. (1976), for example, found that large masses of low-visibility air can be tracked as entities for several days, using only the routine synoptic observations. Furthermore, there was evidence that the areally extensive turbidity reflected the existence of a large number of sulfate aerosols, whose particle size distribution shows a peak between 0.05 and 1 μm (see, for example, Wilson, et al., 1976). The correlation between atmospheric visibility (and turbidity) and sulfate concentration, both of which exhibit regional characteristics, leads therefore to the present attempt to find a qualitative correspondence via the remotely-sensed medium.

The case selected for analysis originated from ERT's data base which is derived from the Electric Power Research Institute, Sulfate Regional Experiment (EPRI/SURE) program, several Tennessee Valley Authority (TVA) stations, as well as from the National Air Sampling Network (NASN) stations. The sulfate measurements taken at all stations consist of 24-hour average values obtained by chemical analysis of high-volume particulate filters. This high sulfate episode over the northeastern United States, for which data existed in the ERT data base and correlative satellite imagery was found to exist, occurred during the period of 8-10 July 1974. The comparison of this high sulfate episode with the corresponding satellite data and associated meteorological conditions is discussed in the following section.

4.2 Comparison of 8-10 July 1974 High Sulfate Episode with Correlative Satellite Data and Meteorological Conditions

Analysis of sulfate levels during this period, as derived from the ERT data base, showed that this episode, which actually began about 4 July over the Ohio Valley, reached a peak on 8 and 9 July over West Virginia, Pennsylvania and New York. By 10 July, the geographical peak had subsided over the Ohio Valley, but a new episode had developed along the middle Atlantic coastal region northward into southern New England.

Figure 4-1 shows the analysis of 24-hour average sulfate levels over the region on 8 July. Concentrations as high as 40 $\mu g/m^3$ are observed over southwestern Pennsylvania and the Ohio-West Virginia border. The four statute mile visibility isopleth is also indicated and shows a generally good agreement with the location of the maximum sulfate levels.

The DMSP daytime visible-to-near infrared channel image and corresponding daytime thermal infrared image of 8 July are shown in Figures 4-2 and 4-3, respectively. The visible-to-near infrared image shows mostly cloud-free conditions over the region of high sulfate concentrations but does not indicate any variations in reflectance that could be attributed to the high sulfate concentrations. In the thermal infrared, however, an overall increase in brightness is observed over the region. This increase in brightness (lower temperatures) suggests that the radiometer is measuring, at least in part, the emittance of the top of the pollutant/haze/smoke layer rather than the surface. In addition, the daytime surface temperatures beneath this layer averaged 4°F to 8°F lower than in surrounding, unobscured areas, thus contributing to the depressed thermal response in the imagery.

The analysis of the 24-hour average sulfate levels over the region on 9 July, shown in Figure 4-4, reveals an overall increase in maximum concentrations with levels as high as 75 $\mu g/m^3$ over western Pennsylvania and 48 $\mu g/m^3$ over West Virginia. The four statute mile visibility isopleth is also indicated and again shows a generally good agreement with the location of maximum sulfate concentrations.

Enlargements of portions of the DMSP daytime visible-to-near infrared band and corresponding daytime thermal infrared (sulfate analysis superimposed) images of 9 July are shown in Figures 4-5 and 4-6. The visible-to-near infrared image displays small areas of scattered to broken stratocumulus clouds located over portions of New York, Pennsylvania, West Virginia, Ohio and Kentucky but, again, does not display any patterns associated with the area of high sulfates. These clouds also appear very bright (cold) in the corresponding thermal infrared image; in addition, the entire area of maximum sulfate concentrations appears somewhat brighter (colder) on this image than the surrouding cloud-free areas, suggesting once again the presence of high pollution concentrations and low visibilities. In this instance, the brighter pattern in the thermal infrared and the reduced visibilities (four mile visibility isopleth, Figure 4-4) both extend into Michigan and Wisconsin, suggesting that high sulfate concentrations may also have been present in those areas on this date; corroborative ground sulfate measurements were unavailable for these two states.

Analysis of NOAA/VHRR nighttime thermal infrared imagery for 8 and 9 July also showed increased brightness (lower temperatures) within the areas of maximum sulfate concentrations; however, the extremely high contrast of these images made them unsuitable for reproduction, and so they are not shown here.

The meteorological conditions during this period may be summarized as the dominance of a warm and humid, maritime tropical air mass throughout the entire region. On 8 July, a slow-moving cold front extending from Quebec to Minnesota was advancing slowly southward. By 10 July when the mid-Atlantic coast episode occurred, the cold front was situated along an east-west line extending from central New England to Minnesota.

During the early part of the period of 8 and 9 July, the large-scale surface wind flow was light southerly or southwesterly, rarely reaching 10 knots at any reporting station. The fairly persistent wind flow from the south and southwest would qualitatively indicate large-scale transport of pollutants toward the northeast. However, in this episode, the time required for northeastward transport of pollutants would have been so long that pollutant advection alone cannot fully explain the regionality of the sulfate episode. There was probably some in situ pollution development.

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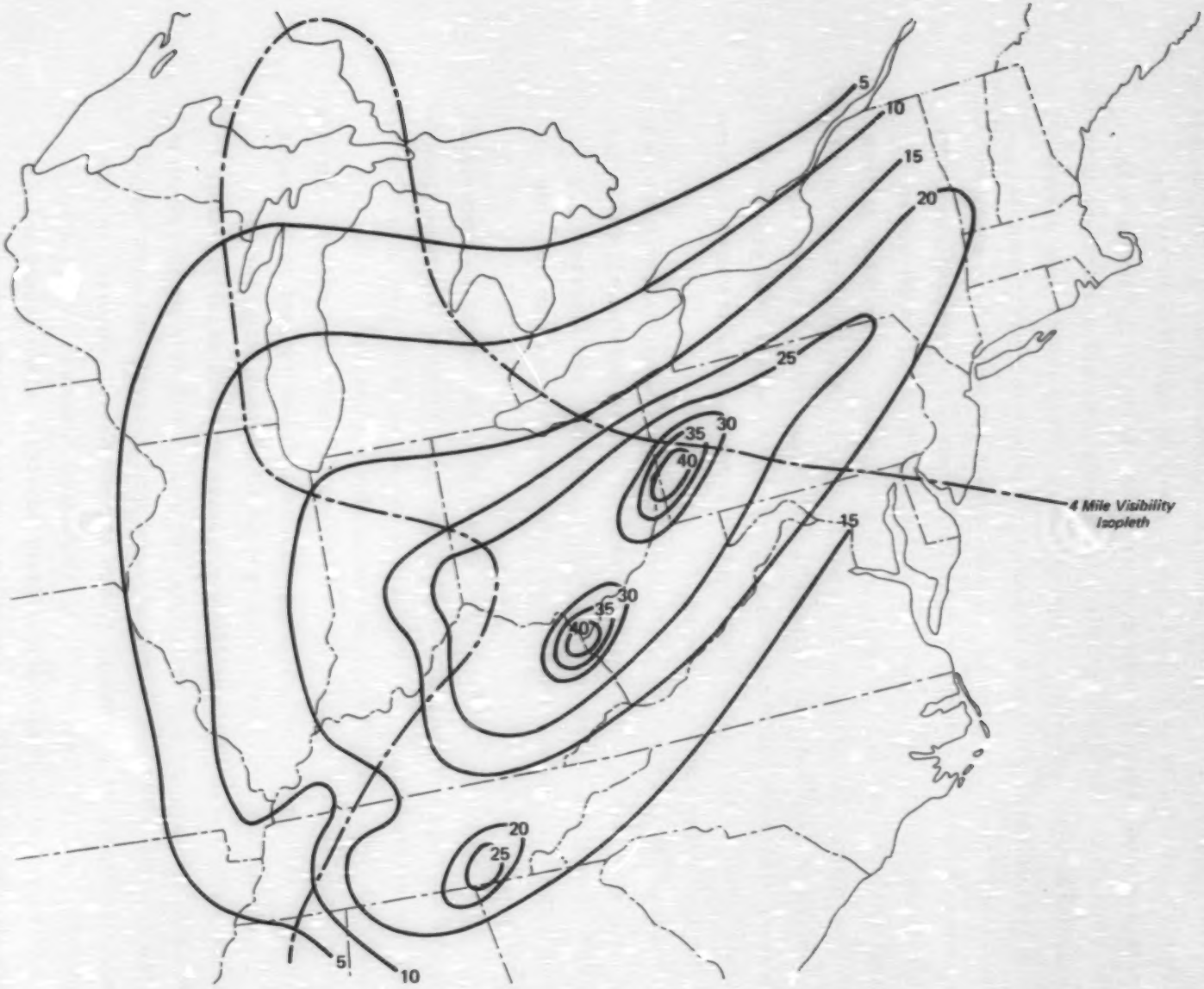


Figure 4-1 Analysis of 24-hour average values of sulfates (ug/m^3) over the northeastern United States on 8 July 1974

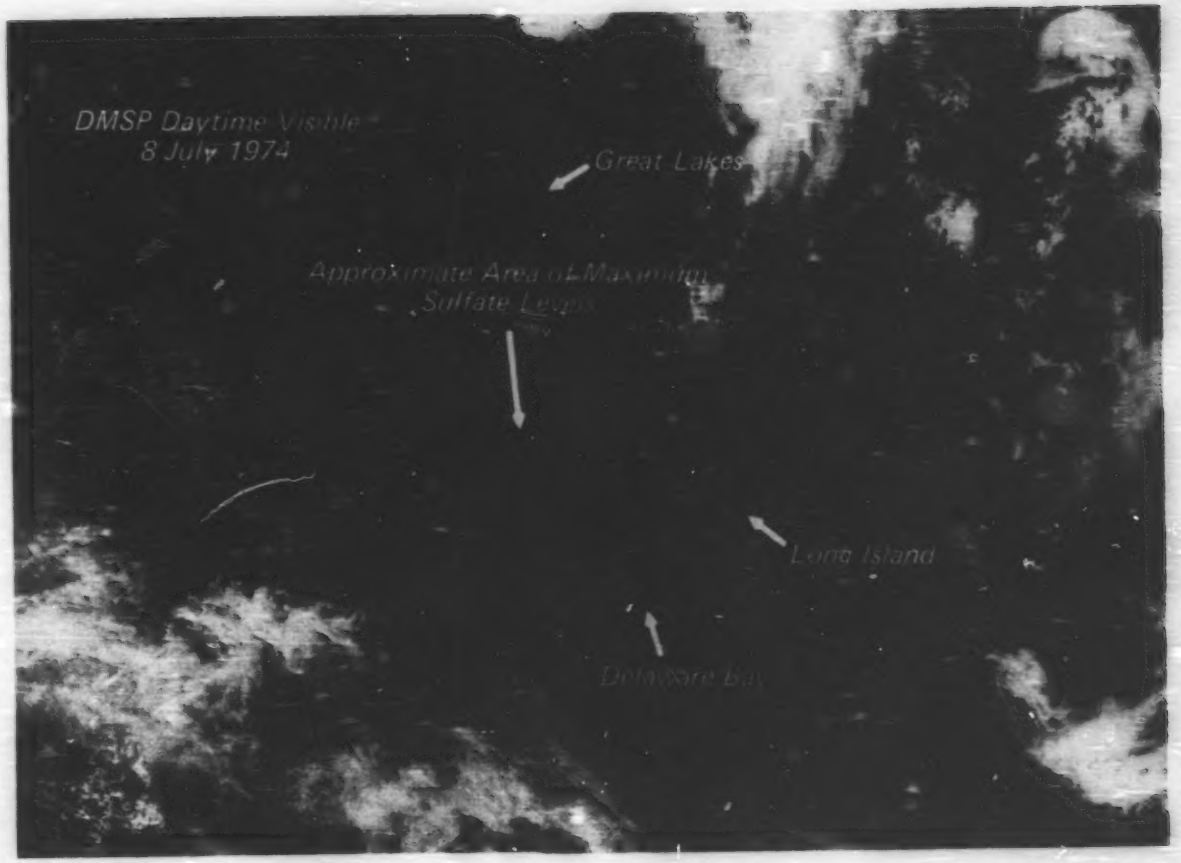


Figure 4-2 DMSP daytime visible-to-near infrared image viewing the northeastern United States on 8 July 1974

ENVIRONMENTAL RESEARCH & TECHNOLOGY INC.

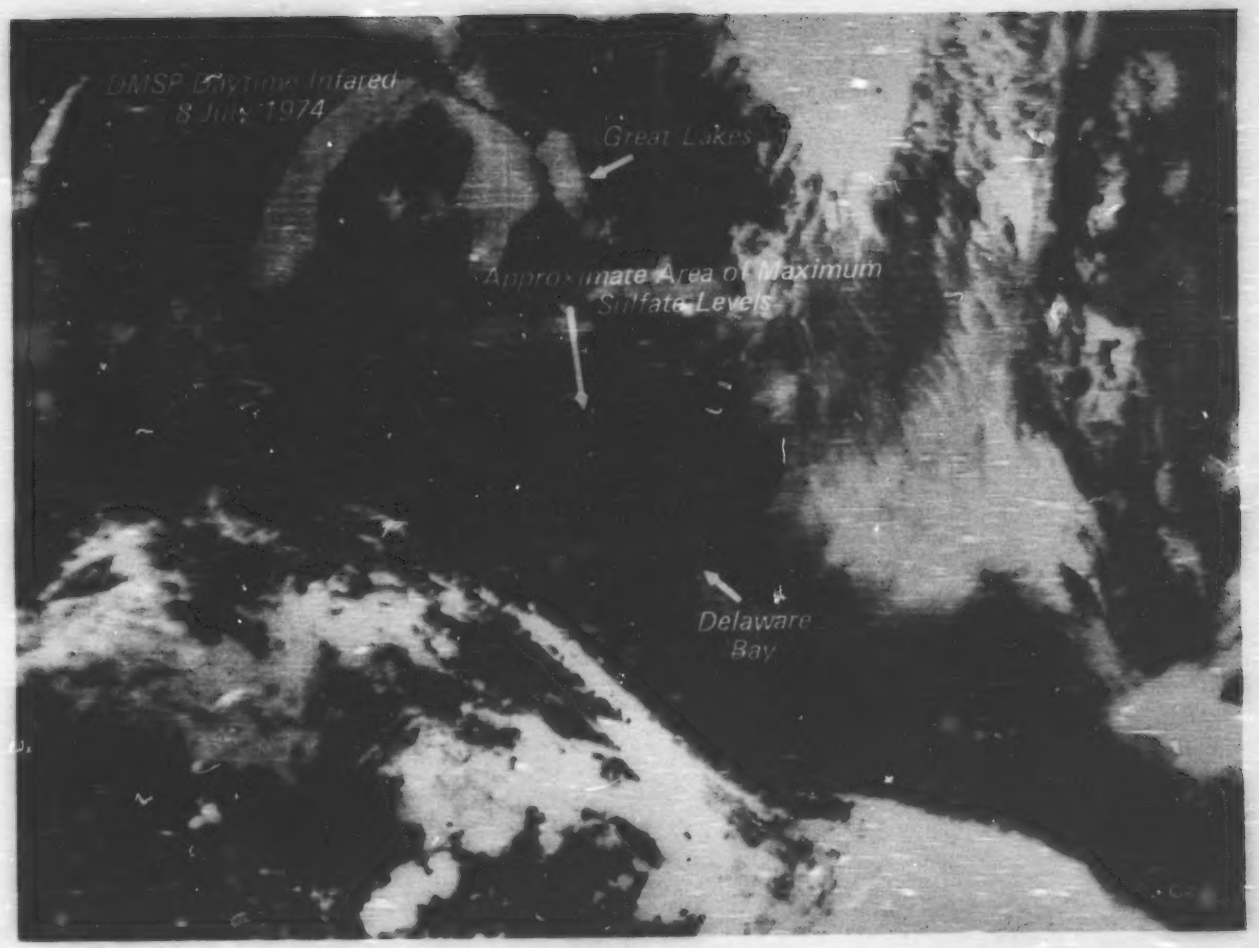


Figure 4-3 DMSP daytime thermal infrared image viewing the northeastern United States on 8 July 1974

ENVIRONMENTAL RESEARCH & TECHNOLOGY, INC.

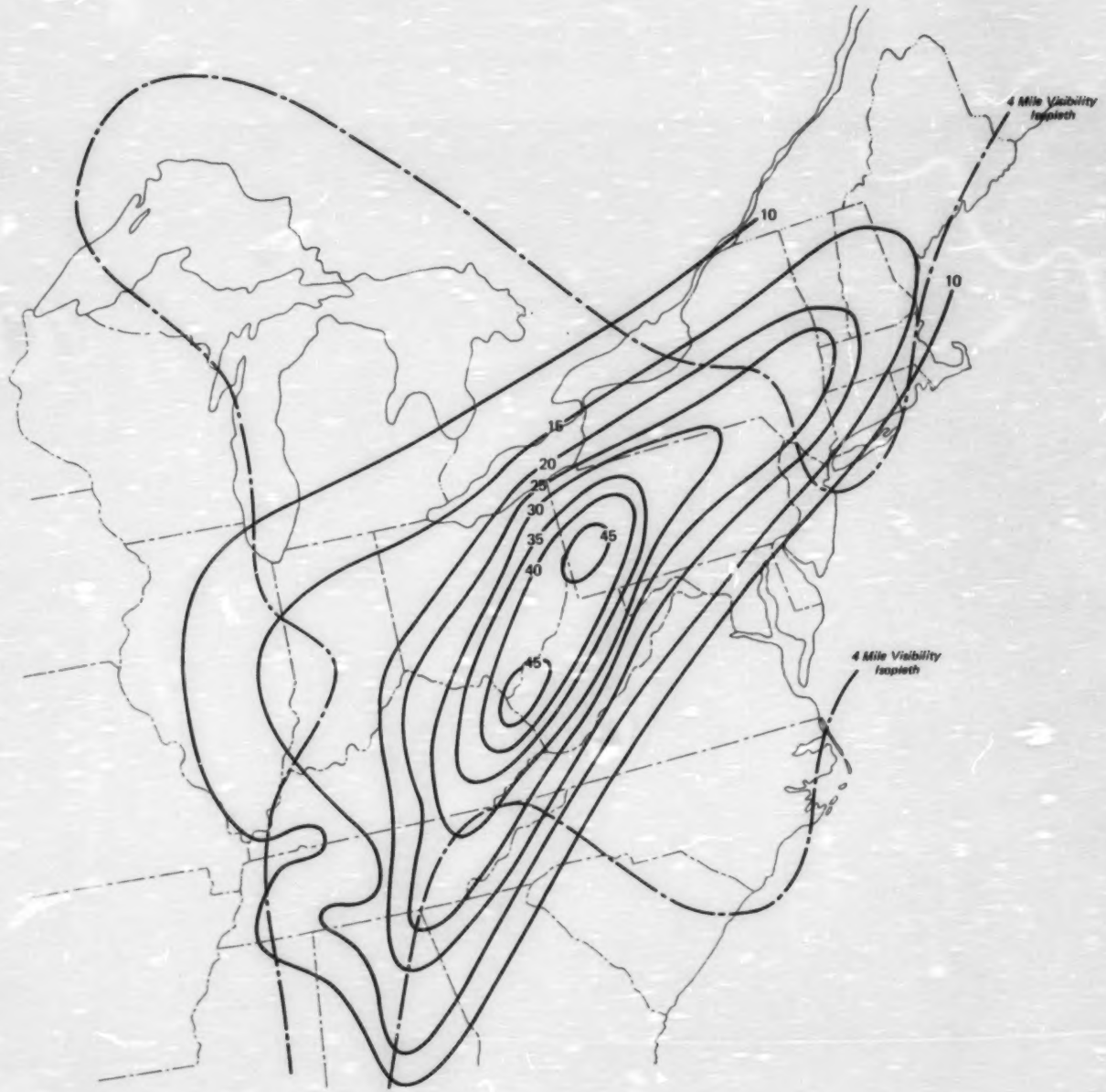
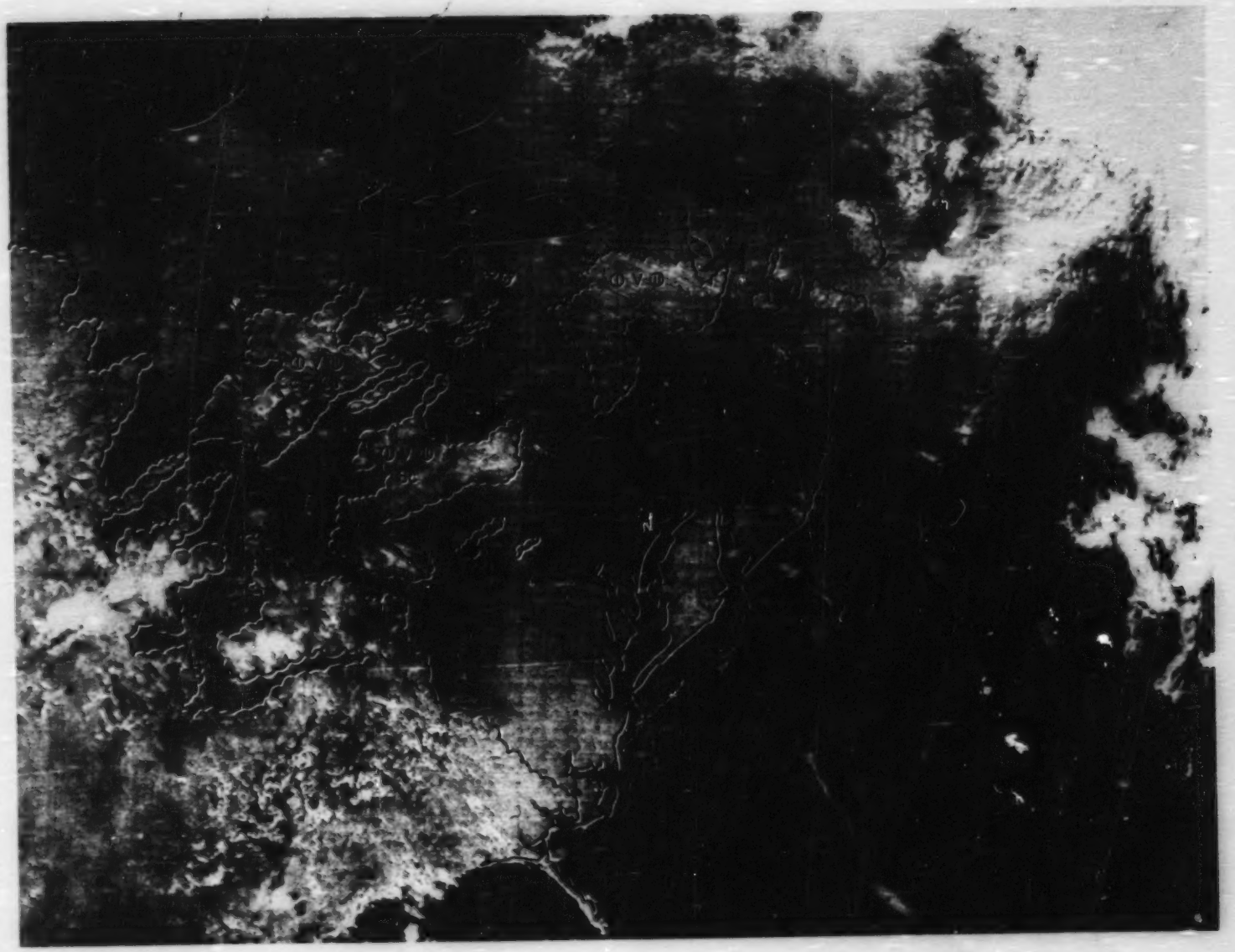


Figure 4-4 Analysis of 24-hour average values of sulfates (ug/m^3) over the northeastern United States on 9 July 1974

ENVIRONMENTAL RESEARCH & TECHNOLOGY, INC.



ENVIRONMENTAL RESEARCH & TECHNOLOGY, INC.

Figure 4-5 Enlargement of portion of DMSP daytime visible-to-near infrared image viewing the northeastern United States on 9 July 1974

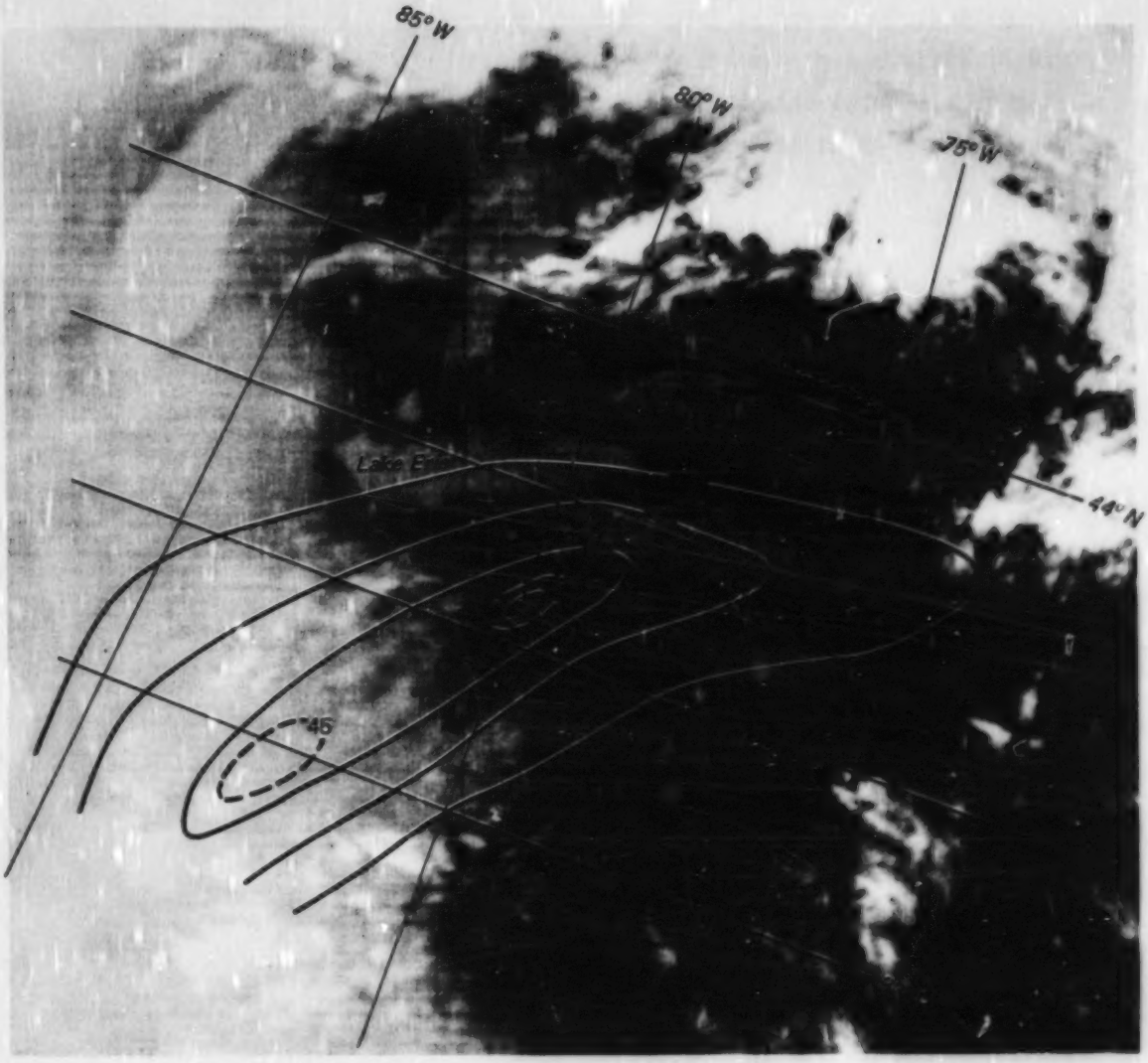


Figure 4-6 Enlargement of portion of DMSP daytime thermal infrared image viewing the northeastern United States on 9 July 1974, with sulfate analysis superimposed

Highest sulfate concentrations were, for the most part, found within the warm, moist air south of the cold front. On each day during the period, the dewpoint temperatures reached 70°F as far north as the mid-Atlantic states along the coast and into the upper midwest region west of the Appalachians. In addition, visibilities were generally less than four miles in haze and smoke over much of the region.

5. SUMMARY AND CONCLUSIONS

5.1 Discussion of Results

5.1.1 Photochemical Oxidants/Ozone

Analysis of three high photochemical oxidant episodes over southern New England indicates a definite diurnal trend with the maximum ozone concentrations occurring in the mid to late afternoon, and minimum levels generally confined to the late night and early morning hours. Unfortunately, the mid-morning readout times of the correlative Landsat images did not coincide with these afternoon peak levels; nevertheless, the ozone concentrations at the time of the satellite passage (1400-1500 GMT) generally exceeded the national ambient air quality primary and secondary standards of 0.080 ppm over much of southern New England.

Throughout each of the periods examined, broad scale haziness resulting in reduced visibilities accompanied the high ozone events. Analyses of the locations of minimum visibilities in haze and smoke across southern New England were found to compare well with the locations of peak ozone concentrations.

Although, for the most part, the areas of the maximum ozone concentrations and haziness were not discernible in the correlative Landsat imagery, some increased reflectance levels were observed over the darker water areas of Long Island Sound and to the east of Boston near coastal stations that were reporting low visibilities. Over the land areas, any varying degree of image reflectance due to air pollution density or low level haze layer was not discernible due to the highly variable brightness levels associated with various ground-feature reflectances, especially the higher reflectances associated with dense urban development.

Examination of the correlative NOAA/VHRR and GOES satellite data also revealed no features suggesting a relationship to locations of peak ozone concentrations, with one notable exception. In this instance, a NOAA-4 daytime visible image was acquired along a satellite track far enough to the west to display a low sun angle along the mid-Atlantic coastal region northward into southern New England. This resulted in an area of low visibility in haze and smoke (and possibly high ozone concentration) of two to four miles over New Jersey, Pennsylvania, southern

New York and Connecticut being easily detected on the imagery due to illumination by the sun. Sun angle apparently plays a significant role in the capability of satellites to observe high pollutant concentrations and associated low visibilities in the visible portions of the spectrum.

Analysis of the meteorological conditions accompanying each of the three high ozone episodes indicates a strong similarity in overall synoptic pattern. In each case, the episode was accompanied by the dominance of warm, humid tropical air throughout the region. In each case, a nearly stationary high pressure system (anticyclone) was centered over the mid-Atlantic states resulting in the flow of warm, moist air into New England on light to moderate south to southwesterly surface winds. Daytime high temperature readings were generally reported in the mid-80°F to low 90°F range, while corresponding dew point temperatures ranged from the upper 60°F to low 70°F level.

5.1.2 Total Suspended Particulates (TSP)

A lack of correlative Landsat coverage during times of high TSP events over southern New England, as well as cloud contamination when other satellite coverage was available, together with a lack of confidence in the representativeness of a number of the important TSP data readings severely limited this phase of the investigation.

Analysis of one correlative Landsat image that provided coverage during a period of isolated high TSP levels reported over southern New England revealed no distinct boundaries to suggest any association with the location of the maximum TSP concentrations. NOAA/VHRR and GOES imagery for the same period also showed no evidence of high TSP concentrations. It appears likely, however, that the isolated high levels were associated with localized conditions at the location sites of the sensors rather than with a widespread pollution episode, and thus no real test of the value of satellite imagery for high TSP episodes was accomplished in this study program.

5.1.3 Sulfates (SO_4)

The final phase of this investigation involved the detection of high sulfate episodes in correlative meteorological satellite imagery. Although the areas of high sulfate concentrations could not be detected

in the DMSP visible-to-near infrared channel imagery at the time of a high sulfate episode over the Northeast (8-10 July 1974), both the daytime and nighttime DMSP thermal infrared imagery during this period showed an overall increase in brightness (lower temperatures) within regions of peak sulfate concentrations. The lower temperatures observed within the area of high sulfate levels, as compared to other areas, suggest that the satellite sensor was viewing, at least in part, the top of the pollutant/haze/smoke layer rather than the surface. In addition, the daytime surface temperatures beneath this layer averaged 4°F to 8°F lower than in surrounding, unobscured areas, thus contributing to the depressed thermal response in the imagery.

The dominance of a warm, humid, maritime tropical air mass throughout the region of high sulfate levels was observed throughout the period. A persistent, light surface wind flow pattern from the south and southwest indicated large-scale transport of pollutants toward the northeast, as well as in situ development of high pollution concentrations.

5.2 Conclusions and Recommendations

Various types of satellite imagery are capable of detecting the atmospheric conditions associated with some regionalized air pollutant concentration situations. The current study looked at Landsat, NOAA/VHRR, GOES and DMSP imagery products, including portions of the visible, near infrared, and thermal infrared sectors of the spectrum. The small sample size of each imagery type and differing concentrations of various pollutants does not allow any definitive conclusion to be drawn regarding the specific effectiveness of a particular imagery type for a specified pollutant. However, some important general observations may be derived from this study, as follows:

1) It is apparent that there is a good correlation between certain types of high pollutant load (including ozone and sulfates) and haze and smoke, with accompanying reductions in visibility. There is good evidence that satellite imagery can display differences in reflectance (visible) or temperature (thermal infrared) due to some combination of haze, smoke and atmospheric pollutant load, on a regional basis. It does not

appear possible, at this time, to differentiate between pollutant concentrations and haze and/or smoke utilizing only the satellite imagery;

2) It has been found that some types of imagery hold more promise than others for helping to delineate the regional extent of pollution-associated conditions. Landsat visible imagery tends to exhibit so much variability in reflectance levels over land areas that differences in atmospheric conditions, other than cloudiness, are difficult to observe. On the other hand, differences among land features are far less pronounced on some of the smaller scale visible and thermal infrared imagery (NOAA/VHRR and DMSP), due to significantly lower resolutions. These image types provide much better backgrounds on which to detect reflectance and thermal differences resulting from high atmospheric pollution episodes. In addition, sun angle seems to play a significant role in the detectability of pollutant-associated conditions in the visible portions of the spectrum. Of the various combinations of type of episode and imagery analyzed during this project, the greatest promise was shown by the DMSP thermal infrared imagery in application to high sulfate situations;

3) The value of satellite systems for monitoring the regional transport of pollutants ultimately depends on their capability for at least daily repetitive observation, as well as the ability of these systems to temporally coincide their observations with the usual time of day of highest pollutant levels.

It is suggested that further study be made to allow additional specificity and quantification of these conclusions. Since the current investigation was heavily Landsat-oriented, ERT recommends that a further in-depth investigation be made of the smaller scale types of imagery ($\sim$1 km resolution and less) such as NOAA/VHRR, DMSP and GOES for which much greater promise has been shown in the detection and monitoring of pollution-associated situations. A suggested approach to such

a study would be to take several high sulfate episodes over the eastern United States and determine the relative capability of each specific satellite system for delineating and monitoring the movement of the pollutant-laden air. ERT would utilize its extensive and unique data base which is derived from the EPRI/SURE program, several Tennessee Valley Authority (TVA) stations, and the National Air Sampling Network (NASN) stations. As part of this study, a further investigation of the influence of factors such as sun angle upon detection of pollutants within the visible bands of satellite sensors could be undertaken. For this, it would be possible to utilize the GOES imagery, which is available on a half-hourly basis throughout the day. It is also suggested to combine with this program a theoretical analysis of the physics of detecting pollutants from space, to help substantiate the findings of the imagery/field data oriented studies.

An additional topic for investigation could include analysis of selected digitized, computer-compatible data from the NOAA/VHRR and Landsat sensors. This would allow much finer separation of reflectance and thermal levels on the imagery than by visual interpretation. No analysis of digitized data was possible under the scope of the current study. Some further means of extracting more useful information from the Landsat imagery could also be assessed, such as comparing imagery from different MSS spectral bands, perhaps using ratioing techniques, or processing the Landsat imagery photographically in such a way as to subdue earth surface features and enhance atmospheric features.

Since only a very limited sample was available in this study, further investigation should be carried out to assess the utility of satellite observations to detect high TSP episodes. As one possible study, correlative meteorological satellite imagery (NOAA/VHRR and GOES) and available Landsat data obtained during the recent, severe dust storms originating over the widespread drought areas of the southwestern United States (late February 1977) would be analyzed to determine the extent to which the high TSP levels are detectable in the various satellite data. ERT already has seen significant evidence of the dust clouds on both NOAA/VHRR and GOES imagery of this period. Attempts would be made

to obtain sufficient ground truth TSP measurements for comparison with the imagery. An investigation of this type would allow identification of the levels and distribution of TSP necessary for detection by earth observational satellites, as well as determination of to what extent the advection and dispersion characteristics can be monitored by satellite imagery viewing land areas.

The conclusions of the current study demonstrate the vast potential that exists in the realm of satellite remote sensing for detection and monitoring of regional pollutant concentrations. Sufficient evidence has been accumulated here to suggest that the Environmental Protection Agency (EPA) continue to maintain interest, and play a significant role, in the development of the specifications for the use of present and future earth surveillance satellite systems. Only by such continued awareness and involvement will EPA ensure that the potential of these systems will be available in the proper modes and further developed, as appropriate, for EPA operational purposes.

6. REFERENCES

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